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Typical bubble shape estimation in two-phase flow using inverse problem techniques

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ABSTRACT

Two-phase flow models predict different arrangements of gas and liquid, which include the formation of bubbles, slugs and aerated areas. Thus, flow visualization plays a central role in development and refinement of models. Recently, high-speed cameras have enabled the recording of these flows and the challenge is often to extract relevant information from large amounts of data.

This paper analyzes and proposes some schemes to estimate a typical bubble based on flow images. The key idea is to find a bubble image that represents and characterizes the flow conditions. As we show, using simple mean as estimator does not yield meaningful images and can be successfully replaced by median. Finally, observing the power spectral density of individual bubble images, we propose an inverse problem regularizer combined with total variation penalization, which significantly improves image quality and sharpens bubble boundaries.

1. Introduction

Fluid flow is not only present in the environment (such as in rivers and rain) but also occurs in a number of industrial applications. A particular type of fluid flow is gas–liquid two-phase flow, in which gas and liquid simultaneously stream in a pipe or vessel. Examples of such flow are found in boilers (steam-water flow), oil and gas production and chemical reactors. Since two-phase flows often determine safety and efficiency aspects of plants and processes, their study and modeling, allied to the development of prediction tools (computer simulators) has been increasingly requested from industry needs.

Nevertheless, models and predictions are only accepted for industrial use when sufficiently validated and tested in pilot-plant studies. Here, special measuring techniques are required for the investigation of two-phase flows. Optical visualization is probably the first diagnostic tool chosen when two-phase flows are investigated. High-speed cameras are easy to operate and typically reach frame rates of tens of kilohertz. Thus, by proper image processing algorithms, optical visualization techniques are useful to investigate the form and behavior of bubbles (e.g. shape, size, velocity), as well as phase boundaries in gas–liquid flows. Such techniques have been very frequently reported in the literature [1,2].

Two-phase flow can manifest itself in many configurations. Fig. 1 exemplifies the possible configurations of two-phase flow depending on individual gas j_G and liquid j_L velocities.

Among these configurations, the so-called slug flow pattern is characterized by a unity cell composed of a liquid slug and an elongated (Taylor) gas bubble, as shown in Fig. 2 [3]. Often, small bubbles can be found in the liquid and become more concentrated towards the air bubble. This subpattern is commonly known as aerated slug flow and often imposes difficulties in visualization. This work is mainly concerned with those types of slug flow in horizontal pipes.

By using the same experimental data, this paper extends our previous results on image processing of slug flows [4] by associating regularization and inverse problems techniques to further enhance the estimates. Basically, we try to impose characteristics of individual pictures to the final estimate in order to get more realistic typical bubble pictures.

2. Related work

Many techniques have already been proposed to analyze and visualize two-phase flow. Those include wire-mesh sensors [5], conductive and capacitive probes [6,7], ultrasound transducers [8], optical tomography [9], X-ray [10] and gamma-ray tomography [11], and high-speed camera [12].

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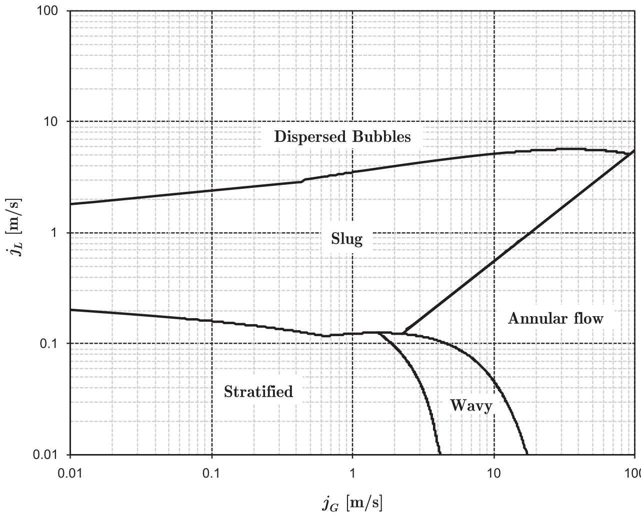

Fig. 1. Taitel flow map [3]. Different individual gas j_G and liquid j_L velocities are predicted to generate different flow patterns.

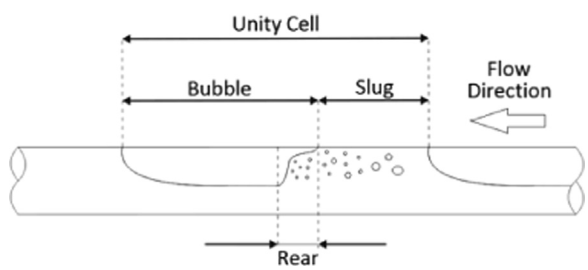

Fig. 2. Basic parts of the unity cell in a slug flow pattern. In this paper, we are interested in characterize the bubble portion of the unity cell. Source: [4].

Van Hout et al. investigated in [13] the translational velocities of elongated bubbles in continuous slug flow for various flow rates, pipe inclination and diameters. As suggested, however, the presence of dispersed bubbles implied in several difficulties to the usage of techniques based on image processing, especially when dealing with aerated flows.

Mayor et al. [12] proposed a technique for automatic analysis of a sequence of video frames with the purpose of object (bubbles) tracking and characterization (dimension, velocity, distance). Although uncertainties were acknowledged, the authors argued that the results followed ongoing trend for image analysis techniques in the study of slug flow patterns. In this study, only non-aerated slug flow was investigated.

Oliveira et al. [14] investigated the shape of elongated bubbles experimentally. They used a set of photo gates for synchronization and, then, averaged in a pixel-wise fashion.

In a recent work [4], our group presented advanced image processing techniques by which it was possible get around previous limitations regarding aerated slug flows. Differently from [14], we did not have at disposal a synchronization mechanism and had to resort to a digital synchronization scheme, which will be better explained in the following sections of this work.

3. Experimental setup

Experimental data were collected in a flow loop located in the Thermal Sciences Laboratory (LACIT) at the Federal University of Technology - Paraná (UTFPR), as illustrated in Figs. 3 and 4.

In this loop, different flow patterns of air and water mixtures are generated in a horizontal acrylic pipe with 9 m of length and

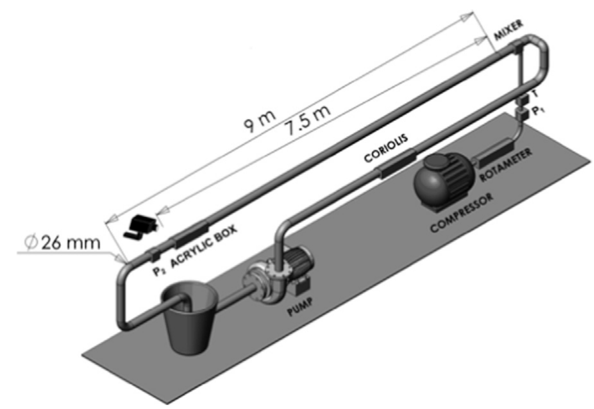

Fig. 3. Schematic of the test loop, comprising a compressor, pump, gauges and a mixer to generate controlled two-phase flow.

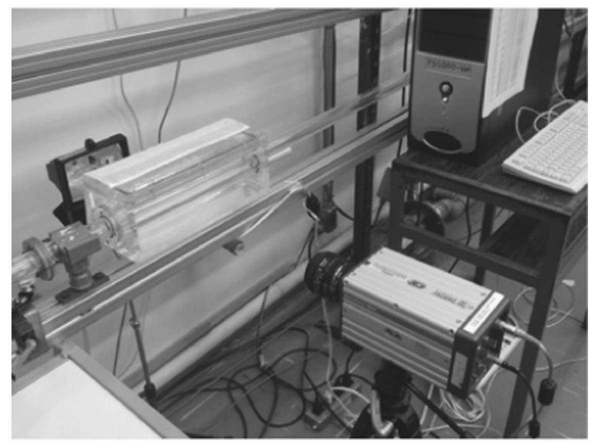

Fig. 4. Video acquisition assembly including a camera, a halogen lamp for background illumination, and acrylic box. Source: [4].

26 mm of internal diameter. A compressor and a pump push air and water, respectively, in a gas–liquid mixer. To ensure flow stabilization, a guard distance of 7.5 m is kept between mixer and measurement point. At the pipe exit, a separator/reservatory expels air to the atmosphere and water is stored and recycled.

Both water and air flow velocities are independently measured before mixing by a Coriolis flow meter (Krohne OPTIMASS 6000, 0.1% accuracy) and a set of calibrated rotameters (nominal accuracy of 1%), respectively.

The flow images are captured by a high-speed camera model NanoSense MKIII (Dantec Dynamics) at resolution 232×500 pixels. The acquisition rate is matched to flow velocity to assure adequate image quality and memory usage.

A rectangular transparent acrylic box (200 mm × 100 mm × 100 mm) filled with water was installed in the recording position to reduce image distortion. A halogen backlight with a diffusive surface was used to ensure uniform illumination.

4. Problem statement

Briefly, we are interested in obtaining a representative bubble image, or *typical bubble image*, for a given pair of liquid velocity and gas velocity, i.e. (j_L, j_G), using image processing techniques. It is worth mentioning that the determination of bubble parameters, such as length or tail angle, is not in the scope of this paper. Rather, we aim to provide a robust estimation strategy to generate typical bubble images for two-phase flow conditions.